Analysis and Synthesis of Data From the WISE/VANS 2005-06 and NLIWI/SCOPE 2007 Field Experiments

Steven R. Ramp
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing, CA 95039
phone: (831) 775-2126 fax: (831) 775-1620 email: sramp@mbari.org

Grant #: N00014-08-1-0393

LONG-TERM GOAL

The long-term goal is to enhance our understanding of coastal oceanography by means of applying simple dynamical theories to high-quality observations obtained in the field. My primary area of expertise is physical oceanography, but I also enjoy collaborating with biological, chemical, acoustical, and optical oceanographers to work on interdisciplinary problems. I collaborate frequently with numerical modelers to improve predictive skill for Navy-relevant parameters in the littoral zone.

OBJECTIVES

The objective of this grant is to improve understanding of how the large-amplitude internal waves and tides in the northeastern South China Sea are generated via interaction of the barotropic tide with the ridges and islands in the Luzon Strait. In addition to the problem's inherent scientific interest, understanding the generation problem is essential for developing a forecast model to predict the wave characteristics in the deep basin and on the Chinese continental slope and shelf.

APPROACH

The approach is to analyze two data sets obtained in the South China Sea in the context of large-amplitude, nonlinear internal wave theory. The data sets were obtained during the Windy Islands Soliton Experiment / Variability Around the Northern South China Sea (WISE/VANS) experiment from April 2005 to June 2006 and the Nonlinear Internal Wave Investigation (NLIWI) from April to July 2007. Maximal effort during this work period focussed on writing up the WISE/VANS data for publication, with emphasis on the seasonal climatology of wave occurances. We also collaborated frequently with Oliver Fringer and PhD student Zhonghua Zhang at Stanford to understand the SUNTANS numerical model runs.

WORK COMPLETED

The WISE/VANS field work was successfully completed during five cruises on board the Taiwanese research vessel OCEAN RESEARCHER 1 during April 2005 to June 2006. The work was staged out of National Sun Yat-sen University (NSYSU) in Kaohsiung, Taiwan, where the support for U.S. scientists was outstanding. Taiwanese graduate students from National Taiwan University (NTU) and

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Analysis and Synthesis of Data From the WISE/VANS 2005-06 and NLIWI/SCOPE 2007 Field Experiments**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Monterey Bay Aquarium Research Institute,7700 Sandholdt Road,Moss Landing,CA,95039**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

NSYSU participated in all cruises. Prof. Y. J. Yang served as Chief Scientist on four cruises with Prof. S. R. Ramp as the lead American. On the February cruise, Prof. Wen-Ssn Chuang served as Chief Scientist and Prof. Ching-Sang Chiu was the lead American. An outstanding data set was collected (Figure 1). Many oral presentations have been made at national meetings, and three papers have been accepted for publication (see below). One additional paper is in advanced preparation. The plan is to move on to publishing the NLIWI/SCOPE results once the primary WISE/VANS paper is completed and accepted.

RESULTS

The successful collection of a full year time series of current, temperature, and salinity across the entire northeastern South China Sea from the Luzon Strait to the Chinese continental shelf has yielded as fascinating collection of new results. A few of the most exciting results are enumerated here and described in greater detail in [Ramp et al., 2009].

- Large nonlinear internal waves (NLIW) were observed traversing the sea with remarkable regularity in all seasons, however these waves were rare during the December – February time period. The lack of waves in winter is attributed to a deep mixed layer and weaker stratification in the upper ocean which cannot support wave propagation (Figure 2).
- The data support the earlier conclusions [Ramp et al., 2004] that there are two kinds of waves generated, the a-waves and b-waves. The present analysis extends those results to show that the a-waves likely begin life as lee waves in the Luzon Strait which are generated on the ebb tide, while the b-waves are released on the flood tide. The b-waves, which appear between the a-wave packets near spring tide, likely result from nonlinear steepening of the (weaker) internal tide formed during the flood tide in the Luzon Strait (Figure 3).
- Both types of waves travel faster (323 cm s^{-1}) in the deep basin than on the continental slope (222 cm s^{-1}), and 9-23% faster than the expected linear mode-1 wave speed (Figure 4).
- The a-waves form only when a critical speed of about 71 cm s^{-1} is exceeded by the ebb tide in the Luzon Strait. This suggests a critical Froude Number, and that hydraulic control may be active in the generating strait (Figure 3). More work is needed to confirm this idea.
- The three-dimensional wave field is advected about by the mesoscale currents along the propagation path, such that northward (southward) currents cause larger (smaller) waves to be observed at the WISE/VANS mooring transect.

IMPACT/APPLICATION

A thorough understanding of the physics of NLIW generation is necessary to achieve reliable predictive skill for the timing and strength of the wave arrivals on the Chinese continental slope and shelf. These results show that the lee wave and non-linear steepening mechanisms are BOTH active in the Luzon Strait, depending on the fortnighly beat and the phase of the tide. The process is modulated by the seasonal variation of the stratification, which determines the strength of the initial interaction with topography and whether trapping of the energy can efficiently take place in the upper ocean along the propagation path [Shaw et al., 2009].

TRANSITIONS

The PI retains a courtesy appointment at the Naval Postgraduate School and has regular contact with the U.S. Navy via officer-students and faculty there. A tactical decision aid consisting of an empirical forecast model for wave arrivals has been developed (C. Jackson, Global Associates) and is being continually refined using our data to determine the positions and times of wave arrivals using realistic stratification along the propagation path. Transitions to SUBPACFLT are anticipated as they become available.

RELATED PROJECTS

A related study to model the SCS waves using primitive equation models is being conducted under NSF Combined Mathematics and Geophysics (CMG) funding. The lead PI on the grant is Prof. Woo-Young Choi, NJIT and it also includes S. R. Ramp (MBARI), D. Lyzenga (UMich) and R. Camassa (UNC). The CMG team has held three successful workshops at NJIT, MBARI, and UNC to bring physical oceanographers and applied mathematicians together. Nonlinear internal waves in the Monterey Bay were also observed during the Adaptive Sampling and Prediction (ASAP) program during August 2006, funded by a DoD MURI grant. The PI also holds a small award ($20K) for the closely related ONR Internal Waves in Straits (IWISE) experiment. No expenditures were made under that award under this evaluation and reporting period.

REFERENCES

Ramp, S.R., C. S. Chiu, H.-R. Kim, F. L. Bahr, T.-Y. Tang, Y. J. Yang, T. Duda, and A. K. Liu, 2004: Solitons in the Northeastern South China Sea Part I: Sources and Propagation Through Deep Water. *IEEE/J. Oc. Eng.*, **29**, 1157-1181.

Shaw, P.-T., D. S. Ko, and S.-Y. Chao (2009), Internal solitary waves induced by flow over a ridge: With applications to northern South China Sea, *J. Geophys. Res.*, **114,** C02019, doi:10.1029/2008JC005007.

PUBLICATIONS

Ramp, S. R., 2008: "Nonlinear internal waves in the South China Sea – An Update." Stanford University, October 2008.

Ramp, S. R., 2008: "Observations of Large-Amplitude, Nonlinear Internal Waes in the Northeastern South China Sea." ICMS Workshop on Large Amplitude Internal Waves, Edinburgh, Scotland, Dec. 1-8, 2008.

Ramp, S. R., 2008: "The influence of hydraulic control on internal wave generation in the Luzon Strait, South China Sea." AGU Ocean Sciences Meeting, San Francisco, CA, December 2008.

Ramp, S. R., 2009: "The influence of hydraulic control on internal wave generation in the Luzon Strait, South China Sea." ONR IWISE planning workshop, Honolulu, HW, January 2009.

Ramp, S. R., 2009: "It's all in the tides." Oral presentation at the 3rd NSF CMG nonlinear interanal waves workshop, Chapel Hill, NC, April 2009.

Ramp, S. R., 2009: "It's all in the tides: More thoughts on a-waves vs. b-waves." ONR Annual Review, Chicago, IL, June 2009.

Li, Q., D. M. Farmer, T. F. Duda, and S. R. Ramp, 2008: Acoustical measurement of nonlinear internal waves using the inverted echo sounder. *J. Atm. and Oc. Tech*. **26**, 2228.

Alford, M. H., R.-C. Lien, H. Simmons, J. Klymak, S R. Ramp, Y.-J. Yang, T.-Y. Tang, D. Farmer, and M.-H. Chang, 2009: Speed and evolution of nonlinear internal waves transiting the South China Sea. *J. Phys. Oceanogr.* Submitted.

Yang, Y. J., Y. C. Fang, M.-H. Chang, S. R. Ramp, C.-C. Kao, and T.-Y. Tang, 2009: Observations of second baroclinic mode internal solitary waves on the continental slope of the northern South China Sea. *J. Geophys. Res*., in press.

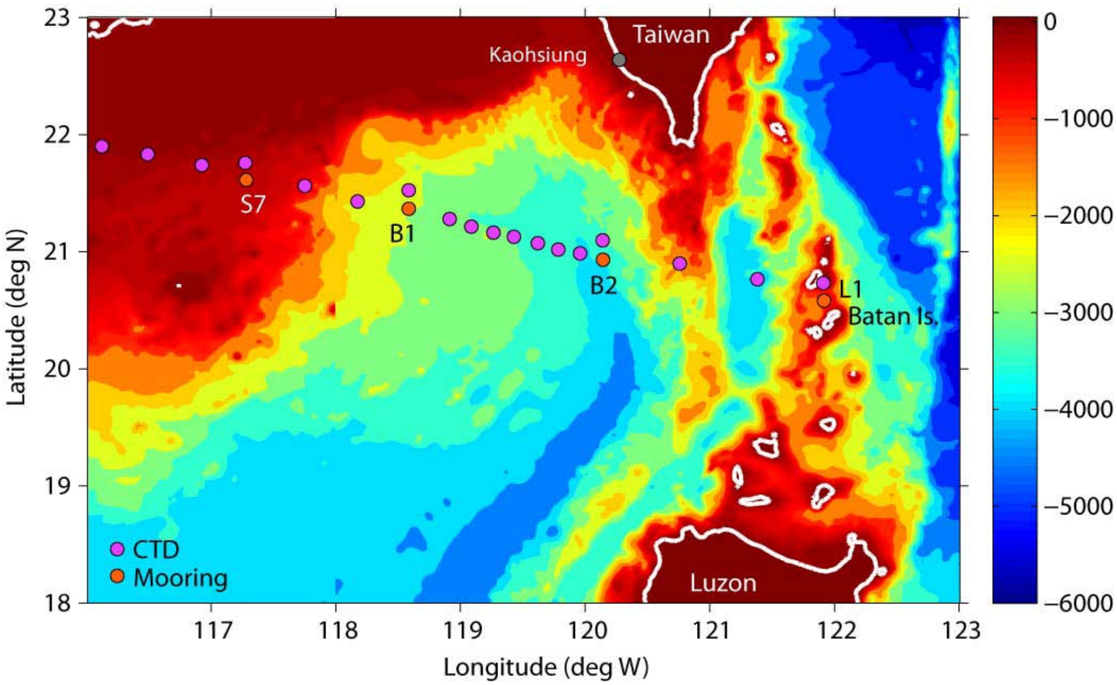

Figure 1. Locator map showing asset locations during the WISE/VANS experiment from April 2005 to June 2006 in the South China Sea. Moorings and CTD stations are indicated by the red and magenta dots, respectively. The background color indicates bottom depth according to the color bar at right.

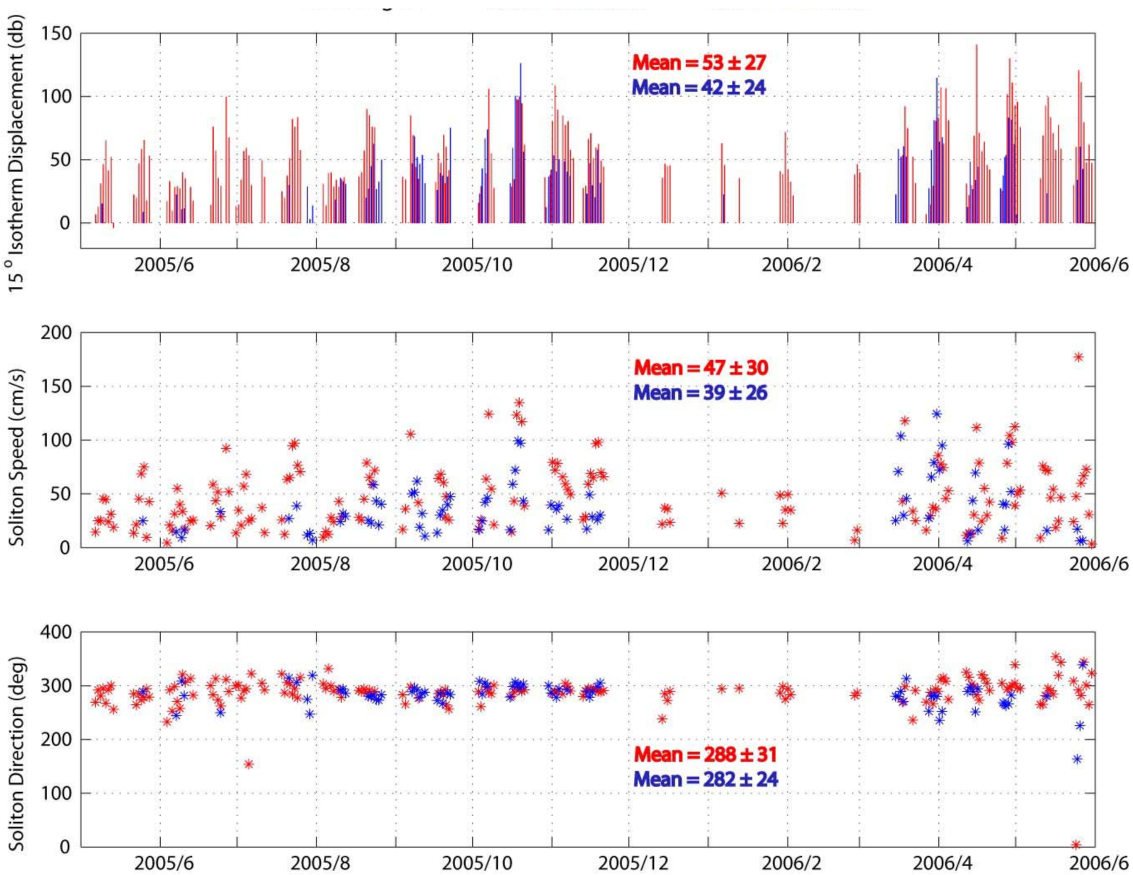

Figure 2. The amplitudes (top panel), maximum upper layer orbital velocities (middle panel) and directions (bottom panel) for all the waves observed during the WISE/VANS experiment. The a-waves are shown in red and the b-waves in blue.

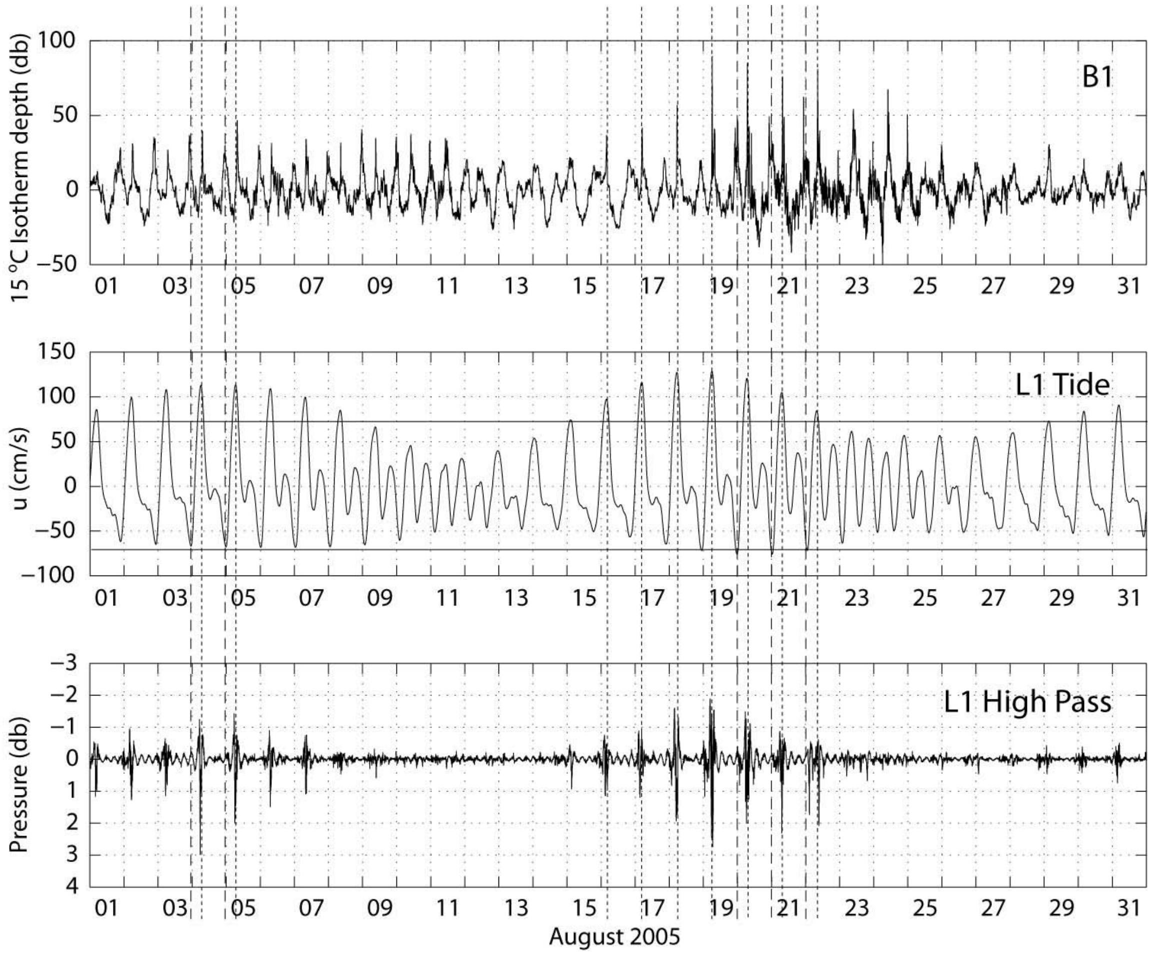

Figure 3. The 15°C isotherm displacements at mooring B1, lagged back 33 hours to account for the propagation time from mooring L1 to B1 (top). The Foreman reconstruction of the tidal currents at mooring L1, using the vertically averaged data (middle). The high-passed pressure data from mooring L1, 410 m depth (bottom). The vertical dotted lines indicate the time of a-wave arrivals at mooring B1, and the dashed lines are the b-wave arrivals. The horizontal lines on the middle panel indicate plus or minus 71 cm s^{-1}.

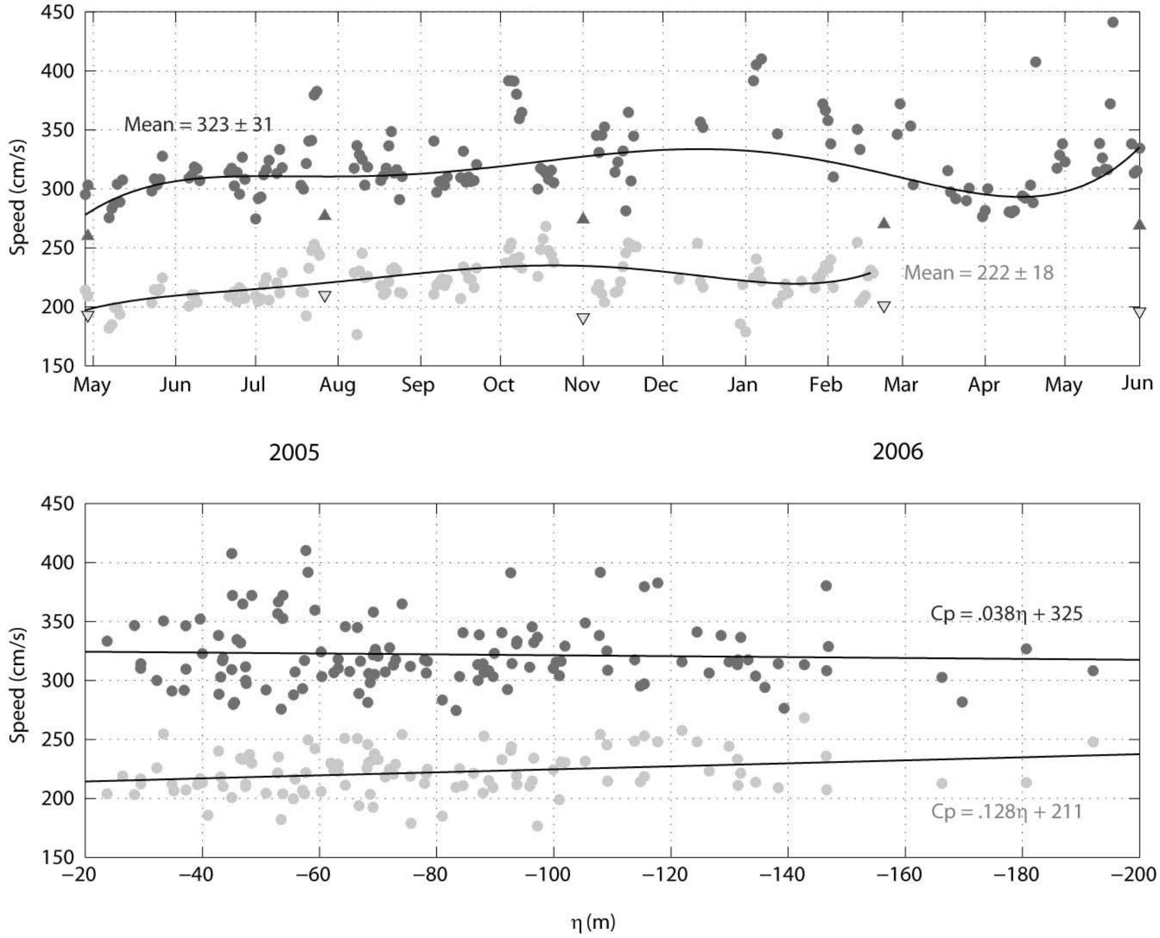

Figure 4. Observed and computed phase speeds of the nonlinear waves as a function of a) time and b) non-linear wave amplitude. The observed phase speeds were computed by tracking the waves between moorings B2 and B1 (black dots) and B1 and S7 (gray dots). The theoretical mode-1 linear phase speeds (triangles) were computed from the CTD data.